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Quantifying Land and People Exposed to Sea-Level Rise with no Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300

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Key Points:
- Even with climate change mitigation, sea-levels and associated hazards will continue to rise for centuries; adaptation remains essential
- Temperature stabilization at 1.5°C and 2.0°C lead to similar levels of exposure for flood plain area and population even at 2300
- However, both have a lower magnitude of sea-level rise and range of uncertainty from a non-mitigation scenario, especially beyond 2100

Supporting Information:
- Figure SM1.
  Figure SM2.
  Figure SM3.
  Figure SM4.
- Supporting Information S1.
- Supporting Information S2.

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Abstract We use multiple synthetic mitigation sea-level scenarios, together with a non-mitigation sea-level scenario from the Warming Acidification and Sea-level Projector model. We find sea-level rise (SLR) continues to accelerate post-2100 for all but the most aggressive mitigation scenarios indicative of 1.5°C and 2.0°C. Using the Dynamic Interactive Vulnerability Assessment modeling framework, we project land and population exposed in the 1 in 100 year coastal flood plain under SLR and population change. In 2000, the flood plain is estimated at 540×10^3 km^2. By 2100, under the mitigation scenarios, it ranges between 610×10^3 and 640×10^3 km^2 (580×10^3 and 700×10^3 km^2 for the 5th and 95th percentiles). Thus differences between the mitigation scenarios are small in 2100. However, in 2300, flood plains are projected to increase to between 700×10^3 and 960×10^3 km^2 in 2300 (610×10^3 and 1290×10^3 km^2) for the mitigation scenarios, but 1630×10^3 km^2 (1190×10^3 and 2220×10^3 km^2) for the non-mitigation scenario. The proportion of global population exposed to SLR in 2300 is projected to be between 1.5% and 5.4% (1.2%–7.6%) (assuming no population growth after 2100) for the aggressive mitigation and the non-mitigation scenario, respectively. Hence over centennial timescales there are significant benefits to climate change mitigation and temperature stabilization. However, sea-levels will continue to rise albeit at lower rates. Thus potential impacts will keep increasing necessitating adaptation to existing coastal infrastructure and the careful planning of new coastal developments.

Plain Language Summary If we reduce greenhouse gas emissions and stabilize global temperatures, sea-level rise (SLR) will continue at a reduced rate for centuries. This is because changes to the ocean and cryosphere (ice) which contribute to SLR take very long timescales to respond to changes in global warming. Early and aggressive climate change mitigation will be most effective to reduce flood risk, particularly after the 21st century. Even with climate change mitigation, the land area exposed to coastal flooding will continue to increase for centuries. Adapting the coast to cope with rising sea levels is inevitably required. The long-term implications for coastal habitation need to be considered.

1. Introduction

Coastal zones are some of the most densely populated areas in the world (McGranahan et al., 2007; Neumann et al., 2015) and have a high concentration of assets. Although sea-level is one of the least responsive climate parameters to react to warming temperatures, it has one of the longest legacies due to the commitment to sea-level rise (SLR) (Nicholls & Lowe, 2004). The commitment to SLR has been recognized in all Intergovernmental Panel on Climate Change assessments (Church et al., 2001, 2013; Meehl et al., 2007; Warrick et al., 1995; Warrick & Oerlemans, 1990), but the impact and adaptation implications have received less attention. The Paris Agreement (United Nations, 2015), aiming to hold temperatures "to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" does not acknowledge the longevity of the SLR threat. Furthermore, given the slow response of SLR to warming temperatures, the immediate differences in sea-level and exposure at 1.5°C and 2.0°C is likely to be relatively small compared to their long-term impacts if temperatures stabilize. However, this has never been quantified.

For the first time, this article will quantify exposure of land and people threatened by coastal flooding, for a wide range of emissions scenarios. In particular it focuses on the differences between the temperature targets of the Paris Agreement (at 1.5°C and 2.0°C) indicative of stringent climate change mitigation. As numerous analyses suggest the 1.5°C target will not be met, and 2.0°C will be challenging (Raftery et al., 2017), we also consider the less stringent mitigation scenarios of 2.5°C, 3.0°C, 3.5°C, and 4.5°C, as well as a scenario where there is no climate change mitigation policy which is associated with higher rises in temperature again. This will be achieved by: (1) introducing the SLR scenarios and the methodology employed to determine exposure in Section 2; (2) analyzing global exposure and the benefits of climate change mitigation in Section 3; (3) determining country level exposure in Section 4; and (4) discussing the implications of these findings in light of the Paris Agreement and adaptive response in Section 5.

2. Materials and Methods

2.1. SLR Scenarios

Global temperature and SLR scenarios were generated in Goodwin et al. (2018a) using an ensemble comprising 5784 simulations from the Warming Acidification and Sea-level Projector (WASP) Earth system model (Goodwin, 2016; Goodwin et al., 2017, 2018b). WASP is an efficient eight-box representation of the atmosphere-ocean and terrestrial carbon system where ensembles are generated such that each of the simulations is observationally constrained (Goodwin et al., 2018a, 2018b). It calculates surface temperature changes due to changes in atmospheric carbon dioxide from cumulative carbon emissions and radiative forcing from other sources (Goodwin, 2016; Goodwin et al., 2015; Williams et al., 2016, 2017). It also projects subsequent changes in sea-level (Goodwin et al., 2017).

Five climate change mitigation scenarios (hereafter known as mitigation scenarios) were developed where temperatures stabilization targets were approximately 1.5°C, 2.0°C, 2.5°C, 3.0°C, 3.5°C, and 4.5°C at different time periods up to 2300. Additionally, one high emissions scenario (hereafter known as the non-mitigation scenario) representative of a policy of no climate change mitigation was constructed. Within the ensemble, each emissions scenario followed the Intended Nationally Determined Contributions (INDC) until 2030 (UNFCCC, 2017). After 2030, the five mitigation scenarios diverge toward different climate stabilization warming targets using a self-adjusting approach to mitigation (Goodwin et al., 2018a). Called adjusting mitigation pathways (AMPs), these scenarios vary the emissions pathway independently in each simulation within the ensemble to steer the simulated warming toward the defined temperature stabilization above preindustrial levels (Figure 1a where the shaded regions indicate uncertainty). The warming trajectories for each AMP thus represent future scenarios whereby concerted political action is taken after 2030 to stabilize climate at the specified warming target (Table 1). The ensemble variation in the warming trajectories for a given scenario then represents uncertainty in climate response to the political action taken over time. We considered climate change projections for seven percentiles of uncertainty (1st, 5th, 17th, 50th, 83rd, 95th, 99th) within the ensemble projections.

Global SLR comprises of two main components: (1) thermostatic expansion and (2) the melting of land-based ice. In WASP, a process-based thermostatic expansion contribution was calculated from an ocean heat uptake model (Williams et al., 2012). The land-based ice melt followed a semi-empirical approach which has previously been used by Rahmstorf (2007) and others. Goodwin et al. (2017) used a constant ice melt coefficient up to 2100, thereafter assuming an exponential decay to zero in 2300. The exponential decay in the rate of SLR from ice melt is set such that the total ice melt contribution to SLR at equilibrium after many thousands of years is 2.3 m/°C (Church et al., 2013).

Figure 1b illustrates future SLR (where the shaded area represents uncertainty in future warming and therefore SLR) and Table 1 illustrates SLR with temperature rise (showing the 50th percentile of temperature and SLR. Brackets in table and subsequent text throughout this article indicate the temperature, SLR or exposure for the 5th and 95th percentiles). Full details of the scenarios (including the range of temperature and SLR under different levels of uncertainty) can be found in the Supporting

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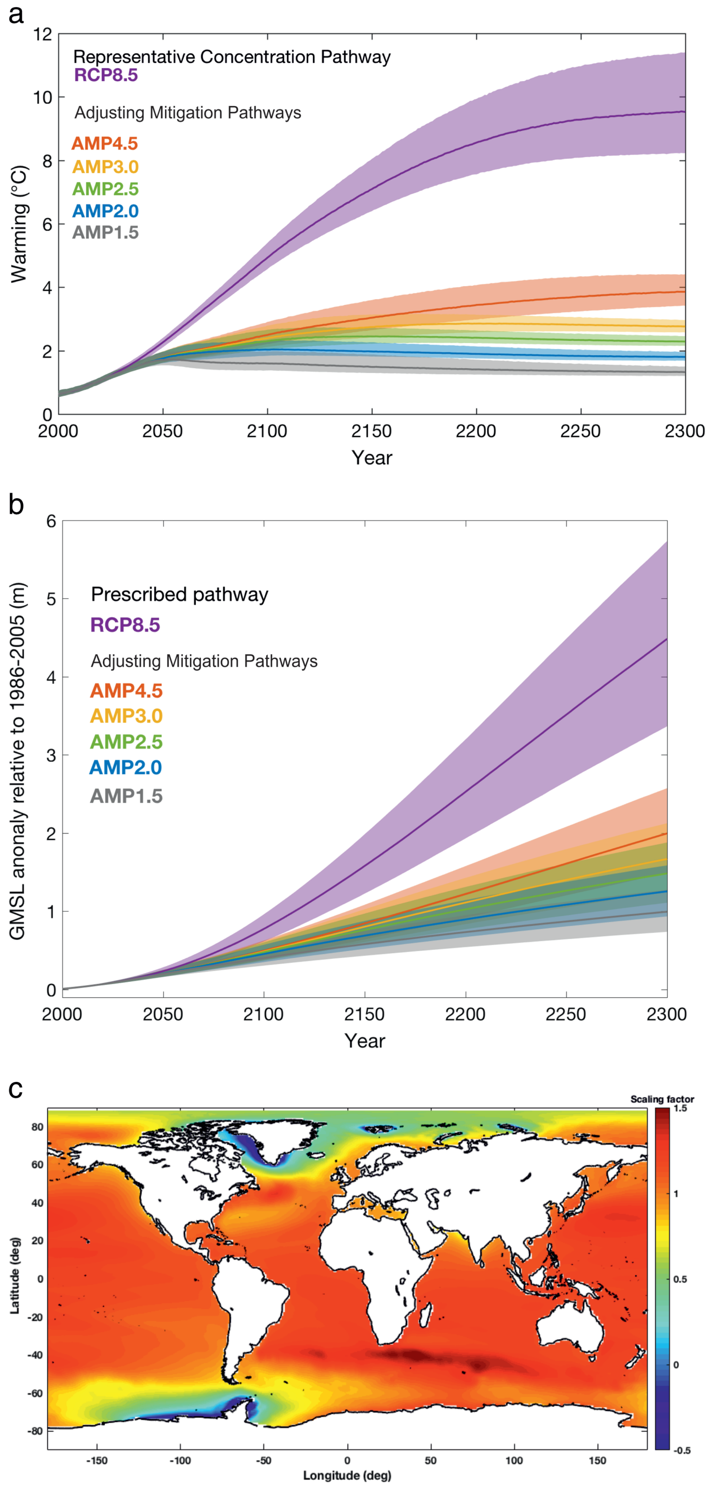

Figure 1. (a) Global mean temperature rise (°C) with respect to pre-industrial developed from an adjusting mitigation pathways approach (AMP1.5, AMP2.0, AMP2.5, AMP3.0, and AMP4.5) and RCP8.5. Shaded areas indicate the 17th to 83rd percentiles (66% range). Data extracted from Goodwin et al. (2018a). (b) Global mean SLR (m) relative to 1986–2005 developed from an adjusting mitigation pathways approach (AMP1.5, AMP2.0, AMP2.5, AMP3.0, and AMP4.5) and RCP8.5. Shaded areas indicate the 17th to 83rd percentiles (66% range). Data extracted from Goodwin et al. (2018a). (c) Normalized pattern of SLR applied to each SLR scenario, based on RCP4.5 from Slangen et al. (2014).

Table 1.
Global Mean Temperature with Respect to Preindustrial (1850–1900) and SLR with Respect to 1986–2005 (50th Percentile, with the 5th and 95th Percentile Range Given in Square Brackets) Extracted from Goodwin et al. (2018a)

		Climate change scenario					
Time	Climate parameter	AMP1.5	AMP2.0	AMP2.5	AMP3.0	AMP4.5	RCP8.5
2050	Temperature (°C)	1.71 (1.44–2.16)	1.76 (1.51–2.16)	1.77 (1.52–2.16)	1.77 (1.52–2.16)	1.78 (1.53–2.15)	2.26 (1.96–2.51)
	Sea-level rise (m)	0.20 (0.14–0.29)	0.20 (0.14–0.29)	0.20 (0.14–0.29)	0.20 (0.14–0.29)	0.21 (0.14–0.29)	0.24 (0.17–0.33)
2100	Temperature (°C)	1.60 (1.26–2.33)	2.03 (1.72–2.64)	2.30 (1.89–2.95)	2.39 (1.97–3.15)	2.50 (2.05–3.28)	4.93 (4.35–5.83)
	Sea-level rise (m)	0.40 (0.26–0.62)	0.46 (0.30–0.69)	0.48 (0.31–0.72)	0.49 (0.32–0.73)	0.50 (0.33–0.75)	0.78 (0.53–1.11)
2150	Temperature (°C)	1.49 (1.19–2.31)	1.97 (1.72–2.68)	2.45 (2.08–3.08)	2.75 (2.24–3.48)	3.04 (2.44–4.15)	7.09 (6.02–8.92)
	Sea-level rise (m)	0.58 (0.35–0.92)	0.69 (0.43–1.06)	0.76 (0.48–1.17)	0.80 (0.51–1.23)	0.85 (0.54–1.30)	1.58 (1.04–2.34)
2200	Temperature (°C)	1.41 (1.15–2.10)	1.90 (1.66–2.57)	2.41 (2.12–3.02)	2.85 (2.40–3.49)	3.44 (2.74–4.66)	8.56 (7.02–11.23)
	Sea-level rise (m)	0.73 (0.47–1.25)	0.90 (0.58–1.50)	1.03 (0.68–1.72)	1.11 (0.75–1.89)	1.22 (0.85–2.13)	2.53 (1.86–4.44)
2250	Temperature (°C)	1.36 (1.13–1.99)	1.83 (1.61–2.41)	2.33 (2.08–2.88)	2.82 (2.48–3.37)	3.71 (3.00–4.81)	9.28 (7.44–12.53)
	Sea-level rise (m)	0.87 (0.51–1.37)	1.09 (0.64–1.66)	1.26 (0.76–1.93)	1.40 (0.85–2.14)	1.61 (0.99–2.49)	3.52 (2.20–5.68)
2300	Temperature (°C)	1.32 (1.12–1.81)	1.80 (1.60–2.20)	2.29 (2.05–2.71)	2.76 (2.45–3.21)	3.86 (3.17–4.75)	9.52 (7.52–13.13)
	Sea-level rise (m)	1.00 (0.59–1.55)	1.26 (0.74–1.90)	1.49 (0.88–2.24)	1.67 (1.00–2.53)	2.00 (1.21–3.06)	4.48 (2.76–6.87)

Information. The median (50th percentile within the 5784 simulation ensemble) properties for each climate stabilization target are as follows (where warming is expressed with respect to preindustrial (1850–1900), and sea-levels are expressed with respect to 1986–2005):

1. AMP1.5: warming initially overshoots 1.5°C, peaking at 1.7°C between the 2040s and the 2060s, before declining to 1.5°C in the 2120s. Warming is 1.6°C in 2100 and 1.3°C in 2300, with SLR of 0.40 and 1.00 m in 2100 and 2300 respectively.
2. AMP2.0: 2.0°C warming reached in the 2070s, with 0.46 and 1.26 m of SLR in 2100 and 2300, respectively;
3. AMP2.5: 2.5°C warming is reached in 2140s with 0.48 and 1.49 m of SLR in 2100 and 2300, respectively;
4. AMP3.0: 2.9°C warming is reached around 2200 with 0.49 and 1.67 m of SLR in 2100 and 2300, respectively;
5. AMP4.5: warming is still increasing at the end of the simulations in 2300, reaching 3.9°C, with 0.50 and 2.00 m of SL in 2100 and 2300 respectively.

For a comparison with a policy of stringent climate change mitigation, a high emissions scenario was generated assuming policies of no climate change mitigation. This is representative concentration pathway (RCP) 8.5, where temperatures reach 9.5°C (7.5°C–13.1°C) in 2300 with 4.48 m (2.76–6.87 m) of SLR. This is compared with Church et al. (2013), where for the same scenario, SLR (5th to 95th percentiles) was projected to be 0.63 m (0.45–0.82 m) by 2100, increasing to 2.26 m (0.92 and 3.59 m) by year 2300. Our new scenarios agree well with Church et al. (2013) to the year 2100 in terms of their lower SLR range, but a have a higher upper range, due to the methodology employed. By 2300, the new scenarios are much higher than Church et al. (2013) because the assumed relationship between temperature and SLR imposed on the model used here gives higher projections than the models applied in Church et al. (2013). Additionally, our scenarios have a lower rise in projected sea-level for the 1.5°C and 2.0°C scenarios in 2100 compared with Jackson et al. (2018). They project median projections of 0.58 and 0.68 m for 1.5°C and 2.0°C scenarios respectively. This is due to the different modeling approaches and techniques used.

Analysis was undertaken for the 1st, 5th, 17th, 50th, 83rd, 95th, 99th percentiles of uncertainty within the SLR scenarios. The scenarios also indicate a large overlap due to uncertainty in both temperature and SLR, which is common in many sets of projections (e.g., Church et al., 2013). For temperature rise, uncertainties overlap for AMP3.0 and AMP4.5 even in the 23rd century. However, in the more stringent climate change mitigation scenarios, the 17th and 83rd percentiles (illustrated in Figure 1a), indicate an overlap until approximately 2150. However, when the 5th and 95th percentiles are considered, an overlap in potential projections continues into the 23rd century. For SLR, all scenarios except RCP8.5, overlap due to uncertainties in projection throughout the timescale of this study. The benefits of mitigation would be increasingly apparent for more stringent mitigation as the uncertainties are resolved sooner in time. Thus for AMP1.5, the uncertainty range is smaller in 2300 than 2050 for temperature, but not for sea-level. Apart from RCP8.5 which represents a clear deviation from the mitigation scenarios, there is no step-change between the remaining scenarios as their uncertainty ranges overlap. Hence this article focuses on the 50th percentile, while considering a wider range of uncertainty.

SLR is not projected to be globally uniform (Brown et al., 2016; Slangen et al., 2014), having implications on country level exposure. Each globally uniform SLR scenario was scaled to the pattern presented in Slangen et al. (2014) which considers oceanic circulation, increased heat uptake, atmospheric pressure, ice and groundwater depletion (glacial isostatic adjustment was not included as this was added during the impacts modeling, see Section 2.3). For the AMP1.5, AMP2.0, AMP2.5, AMP3.0, and AMP4.5 scenarios, comparable SLR patterns are not available from Slangen et al. (2014). Hence we pattern scaled from Slangen et al.'s (2014) RCP4.5 in 2100. RCP4.5 has a similar magnitude of rise to AMP4.5. For our RCP8.5 scenario, we pattern scaled from Slangen et al.'s (2014) RCP8.5 scenario in 2100. Normalized regional differences for Slangen et al.'s (2014) RCP4.5 scenario in 2100 are depicted in Figure 1c (RCP8.5 in 2100 has a very similar normalized pattern). Regional differences indicate the highest rises in the Pacific and off the coast of southern South Africa. The lowest rises are projected in the northern hemisphere, particularly around Greenland.

2.2. Socioeconomic Change Scenarios

Scenarios of socioeconomic change, through the Shared Socioeconomic Pathways (SSP) 1–5 (Moss et al., 2010; O'Neill et al., 2014) illustrate possible changes to population per nation from the present day until 2100 (see Figure S1). SSP1 represents a world where there is sustainability and low challenges for mitigation and adaption, and aligns with climate change mitigation scenarios, such as AMP1.5 or AMP2.0 (which are similar to RCP2.6). SSP4 is akin to inequity where adaptation challenges dominate over mitigation, whereas SSP5 is the opposite. SSP2 represents a mix or intermediate challenges in adaptation and mitigation. In SSP1, 2, 4, and 5 population growth continues until mid-century to approximately 9 billion people, before a steady decline in SSP1 and SSP5, and a slight decline in SSP2 and SSP4. SSP3 represents a fragmented world with multiple challenges in adaptation and mitigation due to high fossil fuel development, where population growth continues throughout the century. This is more likely to be paired with a non-mitigation scenario, such as RCP8.5. Regional variations in population growth and socioeconomic change within each SSP can be important. Given no SSP scenarios exist after 2100, we focus on population exposed up to 2100. Where post-2100 projections are considered, we assume population has not changed since 2100. We recognize that not all SSPs and climate change scenarios can be paired together (Riahi et al., 2017; van Vuuren et al., 2014). For example, SSP1 is not compatible with RCP8.5. These sensitivities are only just being considered (Nauels et al., 2017). Therefore, we have analyzed all as a sensitivity analysis, in part as there are large uncertainties in the climate change scenarios and that some of the deviations in pairings may be more subtle over time depending on the pathway taken.

2.3. Modeling Exposure

We project the area and population living below the 1 in 100 year flood plain via the Dynamic Interactive Vulnerability Assessment modeling framework (DIVA model 2.0.1, database 32) (Hinkel, 2005; Hinkel et al., 2014; Vafeidis et al., 2008). The underlying database (Vafeidis et al., 2008) represents the world's coast as 12,148 linear segments (excluding Antarctica). Each segment has different bio-physical and socioecological characteristics. Land level change takes account of glacial isostatic adjustment based on Peltier (2004). No additional subsidence was assumed in delta regions. Total water levels were extracted from Muis et al. (2016). The distribution of elevation in DIVA is derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model (Jarvis et al., 2008) and the GTOPO30 dataset (USGS, 2015) for areas above 60°N and 60°S. SRTM has a vertical resolution of 1 m and spatial resolution of approximately 90 m at the equator (30 arc sec). For the calculation of population exposed to flooding the Global Rural Urban Mapping Project (GRUMPv1) elevation dataset with a spatial resolution of 30 arc sec was employed (Balk et al., 2006; Center for International Earth Science Information Network — Columbia University (CIESIN) et al., 2011). As we analyze exposure, these estimates do not consider the effects of protection (e.g., dikes, dunes), so these numbers represent indicators of the largest land areas and population potentially threatened by SLR. Actual impacts are dependent on numerous factors, such as the ability of a flood to propagate inland, protection levels or preparedness. Apart from calculating the number of people exposed, our projections are free from socioeconomic change.

3. Global Analysis

3.1. Global Exposure to 2100

The five AMP scenarios and RCP8.5 were combined with socioeconomic scenarios. We project the land area and the number of people living in the 1 in 100 year coastal flood plain from the present day to 2100 (Figures 2a and 2b). Under all scenarios, the area in the flood plain keeps increasing as sea levels rise, particularly under the 95th and 99th percentiles of each scenario. In 2000, the global flood plain area is estimated at 540×10^3 km^2. By 2100, under the climate change mitigation scenarios, the flood plain area ranges between 620×10^3 km^2 (580×10^3 and 670×10^3 km^2) (AMP1.5) and 650×10^3 km^2 (590×10^3 and 700×10^3 km^2) (AMP4.5) and under the non-mitigation scenario increases to 740×10^3 km^2 (650×10^3 and 790×10^3 km^2) (RCP8.5). Differences between the mitigation scenarios are relatively small in 2100, but are more notable when comparing the mitigation scenarios and non-mitigation scenario, particularly when uncertainties in temperature and sea-level are taken into account. However, sea-levels are known to rise and will continue to do so post 2100 (Goodwin et al., 2018a). This will be analyzed in Section 3.3.

The greatest number of people in the flood plain in 2100 is projected for SSP3, and the smallest number for SSP4 (with SSP1 close behind) (Figure 2b). However, SSP4 does not have the lowest global population in 2100 compared with the other SSP scenarios. Hence the regional distribution of people over time is important. Figure 2b illustrates that the number of people in the flood plain depends on socioeconomic conditions and projections of SLR. Compared with global population projections (see Figure S1), people in the coastal flood plain follow a similar trajectory (see Section 2.2). Variations in country level projections are only slightly evident. For example, in 2100 the global projected population is similar in SSP2 and SSP4, but the population in the coastal flood plain differs due to a decrease in the nation population projected in east and south-east Asian countries (which contribute substantially to global exposure), such as Indonesia, Vietnam and China. These nations have a high number of people exposed to flooding. The distribution of regional population (e.g., the population of China in SSP3 which declines at a slower rate than the other socioeconomic scenarios) can make notable differences in the number of people exposed to the hazard (see Section 4.2), more so than SLR.

3.2. Benefits of Climate Change Mitigation in the 21st Century

An important emphasis in the Paris Agreement (United Nations, 2015) is the differences in climate change (including implicitly SLR) between 1.5°C and 2.0°C, and therefore exposure. Temperature projected under the AMP1.5 and AMP2.0 scenarios to not diverge until the 2040s for the 50th percentile. For the 5th and 95th percentiles, projections remain similar at least to the end of the century. Due to the commitment to SLR and INDCs, the magnitude of SLR does not diverge for the full range of uncertainties until the 2050s. By 2100, the difference in SLR between AMP1.5 (representing a 1.5°C scenario) and AMP2.0 (representing a 2.0°C scenario) is 0.06 m (0.04 and 0.07 m) (see Table 1). In terms of exposure, there is only a percentage difference of 3% (for area) and 4% (for population) in 2100. The main benefits of climate change mitigation will be seen after 2100 (see Section 3.3).

Figure 3 illustrates the benefits of climate change mitigation through the percentage of impacts avoided for (1) the coastal flood plain and (2) people located in the coastal flood plain, for AMP1.5 compared with RCP8.5 per SLR and socioeconomic scenario. This calculation was also undertaken with AMP2.0 instead of AMP1.5 but is not shown as the result was very similar. Most differences do not emerge until mid-century as until that time differences in the scenarios are relatively small. This is because of similar emissions to 2030 following the INDCs and due to the commitment to SLR, and also for the population exposed, socioeconomic change. Uncertainties increase with time as the range of projected SLR increases.

In terms of land area, the percentage of exposure avoided for AMP1.5 compared with RCP8.5 (50th percentile) is less than 10% until 2040 (Figure 3a). Here, the temperature difference between the scenarios is approximately 0.1°C and the difference in SLR between the scenarios is 0.01 m. After this point, the

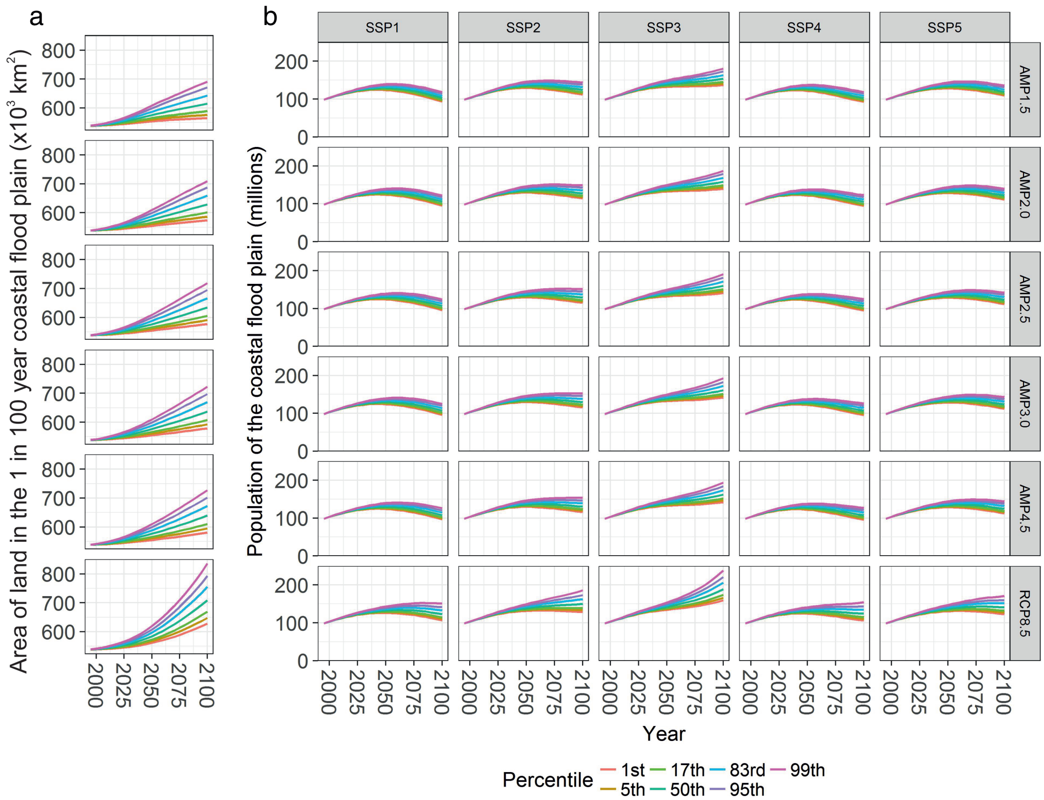

Figure 2. (a) Area of land located in the 1 in 100 year coastal flood plain (socioeconomic scenario independent). (b) Number of people living in 1 in 100 year coastal flood plain. Colors represent the different percentiles of projected SLR within each projected SLR scenario.

rate of avoided area increases, and slowly diverges. By the 2080s, the avoided exposure slows. By 2100, the maximum avoided area exposed is 47% (43%–52%). There are lower variations in uncertainty of the 5th and 95th percentiles of SLR compared with the 50th percentiles due to relative changes in the rate of SLR and land elevation levels. Principally, climate change mitigation is important in reducing exposure.

A similar trend occurs for the percentage of exposure avoided for the people living in the flood plain (Figure 3b). There are only very small differences caused by socioeconomic change. Rather, the variance is caused by the different percentiles of uncertainty in SLR. The maximum avoided exposed population exposed is 50% (52%–47%) in 2100. Thus, compared with a non-mitigation scenario, both AMP1.5 and AMP2.0 bring climate change mitigation benefits by 2100. For some nations and socioeconomic scenarios, this time period coincides with declining populations. Following the findings of Nicholls and Lowe (2004) and Nicholls et al. (2018), these results indicate that as sea-levels will keep rising after 2100. Thus the full benefits of climate change mitigation will not be fully realized until the 22nd century and beyond.

3.3. Benefits of Climate Change Mitigation beyond the 21st Century

To explore the centennial benefits of mitigation, Figure 4 plots the 1 in 100 year flood plain exposed to SLR with (1) temperature rise and (2) SLR from the time period of 2000–2300. These results are independent of population change. The larger the area of the circle, the greater the exposure (note the scale is non linear). The figures illustrate that as time progresses, the area of land exposed increases. Even if global temperature declines with climate change mitigation (as shown with AMP1.5, AMP2.0, AMP2.5, and AMP3.0) there is a commitment for sea-levels to keep rising due to historical warming. Thus the land area exposed continues to increase (Figure 4a). The non-mitigation scenario is very different to the mitigation scenario as globally the rate and absolute magnitude of land exposed continues to increase, particularly after 2100.

In 2000, the area of flood plain is estimated at 540×10^3 km^2. In 2100, the area is projected to be between 620×10^3 and 650×10^3 km^2 (580×10^3 to 700×10^3 km^2) for the mitigation scenarios, but increases to

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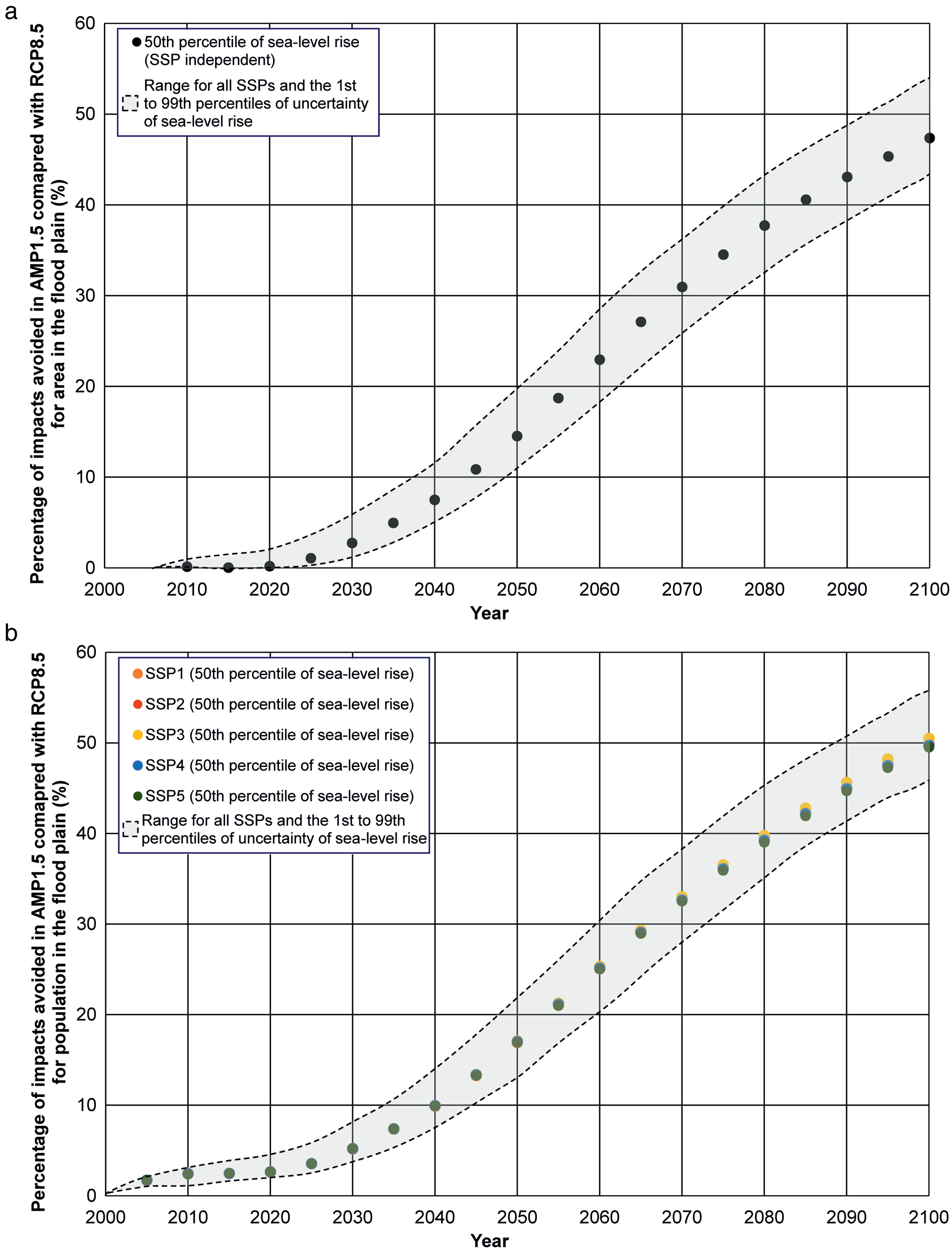

Figure 3. (a) Percentage of area of land located in the 1 in 100 year coastal flood plain avoided for AMP1.5 compared with RCP8.5 (%) per SLR scenario (socioeconomic scenario independent), (b) percentage of people located in 1 in 100 year coastal flood plain avoided for AMP1.5 compared with RCP8.5 (%) per SLR and socioeconomic change scenarios.

740×10^3 km^2 (650×10^3 to 790×10^3 km^2) for the non-mitigation scenario. By 2200 the difference between the mitigation and non-mitigation scenarios (taking account the 5th and 95th uncertainty boundaries) is clearer than 2100: the area of projected flood plain ranges from 660×10^3 to 1110×10^3 km^2 (590×10^3 to 960×10^3 km^2) across all AMPs, while it increases to 1140×10^3 km^2 (890×10^3 to 1490×10^3 km^2) for RCP8.5. By 2300, flood plain area is projected to be between 700×10^3 and 960×10^3 km^2 (610×10^3 to 1290×10^3 km^2) in 2300 for the mitigation scenarios, but 1630×10^3 km^2 (1190×10^3 to 2220×10^3 km^2) for

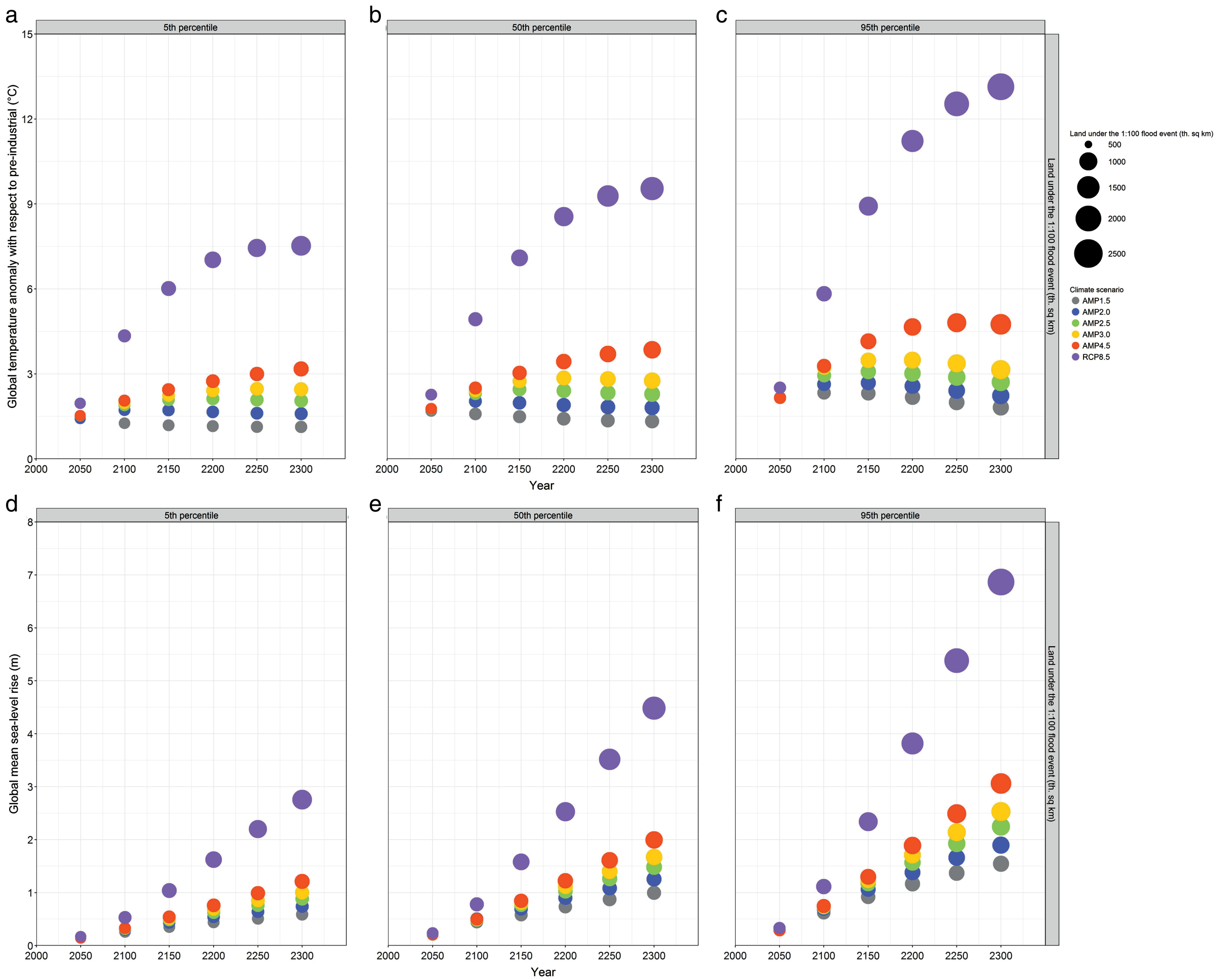

Figure 4. Area of land located in the coastal flood plain per scenario, plotted against time and with global mean temperature rise for the (a) 5th percentile, (b) 50th percentile and (c) 95th percentile; plotted against time SLR and for the (d) 5th percentile (e) 50th percentile, and (f) 95th percentile. Note that the area of the circle does not increase linearly as exposure increases.

the non-mitigation scenario. Climate change mitigation at 1.5°C (50th percentile) can result in avoided land area exposure by up to 79% in 2300. Thus, climate change mitigation and particularly early or aggressive mitigation can avoid large land areas exposed to flooding on centennial timescales.

The coastal zone population living in the flood plain in 2300 cannot be projected as consistent socioeconomic scenarios do not extend this far into the future. However, the magnitude of SLR in 2300 can be reproduced at different time periods up to 2100. This then allows for the calculation of people living in the flood plain at that period under the five SSP scenarios. This calculation was undertaken for the time periods of 2020 and 2100. The projections at 2100 are also representative of the population that could be exposed in 2300 if socioeconomic change is kept constant after 2100. This is shown in Figure 5 for the 5th, 50th, and 95th percentiles. The uncertainties associated with SLR mean an overlap in exposure in different mitigation pathways. The greatest magnitude of uncertainty is for the 95th percentile rather than the 5th percentile.

In 2020, the equivalent number of people living in the flood plain ranges between 190 million (SSP1) to 270 million (SSP3) (160 million to 370 million), representing 2.5%–3.6% (2.1%–4.9%) of global population

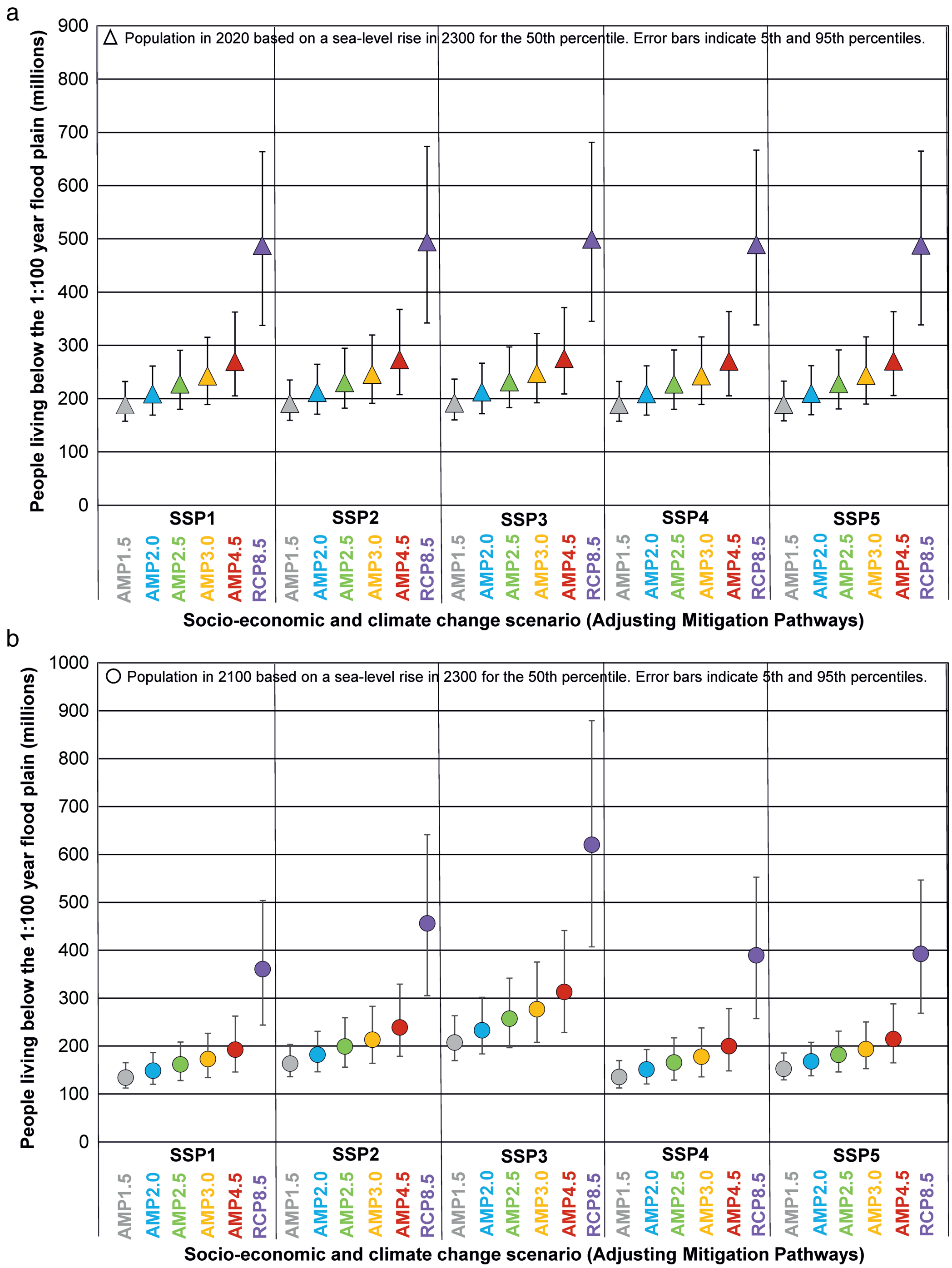

Figure 5. Population living below in the 1 in 100 year coastal flood plain for a SLR projected in 2300 but under socioeconomic conditions in (a) 2020 and (b) 2100.

for the mitigation scenarios. For the non mitigation scenario, this extends up to between 490 to 500 million (350 million to 680 million) (6.4%–6.5% [4.5%–8.9%] of global population). In 2100, this range widens to between 130 million (SSP1) to 310 million (SSP3) (110 million to 440 million), corresponding to 1.5%–2.1% (1.2%–4.0%) of global population under the climate change mitigation scenarios. Absolute numbers decline despite SLR due to falling global population. For the non-mitigation scenario, the range of the equivalent number of people living in the flood plain increases to between 360 million (SSP1) to 620 million (SSP3) (240 million to 880 million), or 4.3%–5.4% (3.7%–7.6%) of global population. The decline in population affected in 2100 is due to global population trends which occurs in all socioeconomic scenarios except SSP3. This is because China, which dominates global population trends has a larger population in SSP3 than in the other scenarios. Therefore future population exposure is highly sensitive to socioeconomic change in addition to SLR, and can dominate changes.

4. Country Analysis

4.1. Area of the Flood Plain Exposed

The top 10 countries with the largest flood plain are shown in Figure 6 in 2100, 2200, and 2300. Figure 6 shows exposure for the 50th percentile only, with the figures for the 5th and 95th percentile available in Supporting Information. For reference, temperature and SLR for each scenario are also shown. The 10 countries most exposed are China, Russian Federation, United States of America, Canada, Brazil, Vietnam, Australia, India, Indonesia, and Mexico. A total of 7 out of 10 nations also have one of the tenth longest coastlines in the world (India, China, and Vietnam have shorter coastlines, but instead have numerous low-lying deltas at risk from flooding).

Figure 6 (and Figures S2–S4) illustrates (through the “No SLR” bar) that large areas of flood plain would be exposed even if sea-levels were not rising. This indicates that defending land is important in many areas today (particularly those with large populations or much economic activity located on the coast) and will continue to be so in the future. Canada and the Russian Federation are the only nations in those presented where land exposed (assuming no SLR) could potentially decrease due to isostatic uplift. Also, SLR is projected to be smaller in north-east Canada than the global mean (see Figure 1c) making this process more acute. Due to changing land levels, Canada is one of the world's least affected nations from SLR per kilometer of coast. For all other nations, even a small magnitude of SLR (e.g., AMP1.5) can result in more land being exposed than the no SLR scenario, even for the 5th percentile of SLR.

By 2100, large differences in the flood plain are not noticeable across scenarios, but by 2300, there are much greater differences due to the commitment to SLR. In 2100, uncertainties in exposure between the 5th, 50th, and 95th percentiles are apparent, and these differences grow in 2200 and 2300. Nationally, these uncertainties are important to recognize. For example, projections indicate that in Vietnam the RCP8.5 scenario (5th percentile) may result in approximately 24×10^3 km^2 of land in the coastal flood plain in 2100. This is similar to the amount of land in the coastal flood plain in an AMP1.5 (95th percentile) scenario. Hence, uncertainties in the magnitude and SLR can be more important than the climate change mitigation pathway taken.

The benefits of climate change mitigation are particularly apparent after 2100 as there is already a commitment to SLR due to past warming. By 2300, the Russian Federation and China are projected to have the largest area of flood plain exposed to the impacts of SLR (although this is also dependent on the scenario and uncertainty considered). In 2300, the additional flood plain exposed under the non-mitigation compared with the climate change mitigation scenarios is particularly acute in India, Indonesia (for all percentiles of uncertainty in SLR) and Mexico (particularly for the 50th and 95th percentile of uncertainty in SLR). While this means India, Indonesia, and Mexico may be relatively less affected if mitigation is successful, if sea-levels keep rising to high levels they may need to consider adaptation solutions where land is valuable and therefore demands protection. Therefore, they will benefit most from aggressive climate change mitigation compared with a non-mitigation scenario. Further research at local levels is required to determine exactly what land would benefit most from protection (see Section 5.1).

Previous research (e.g., Lichter et al., 2010) into exposed land area per meter of elevation in the low elevation coastal zone (land below 10 m above mean sea-level) indicated similar nations are exposed (Mexico, United States, Russian Federation, China), except Indonesia. This may be because of differing elevation models or the total water levels projected.

4.2. Exposed People in the Flood Plain

Nations with a large population exposed to flooding are also considered. The nation with the most exposed population by 2300 (assuming population is maintained at 2100 levels) is China (99 million people in SSP3), followed by Indonesia (94 million people in SSP3) and Bangladesh (57 million people in SSP3). Figure 7 illustrates population located in the coastal flood plain in 2020 under the SLR condition in 2300 for China, Iraq, Canada, and Bangladesh (where the color of each square represents the population exposed in 2020

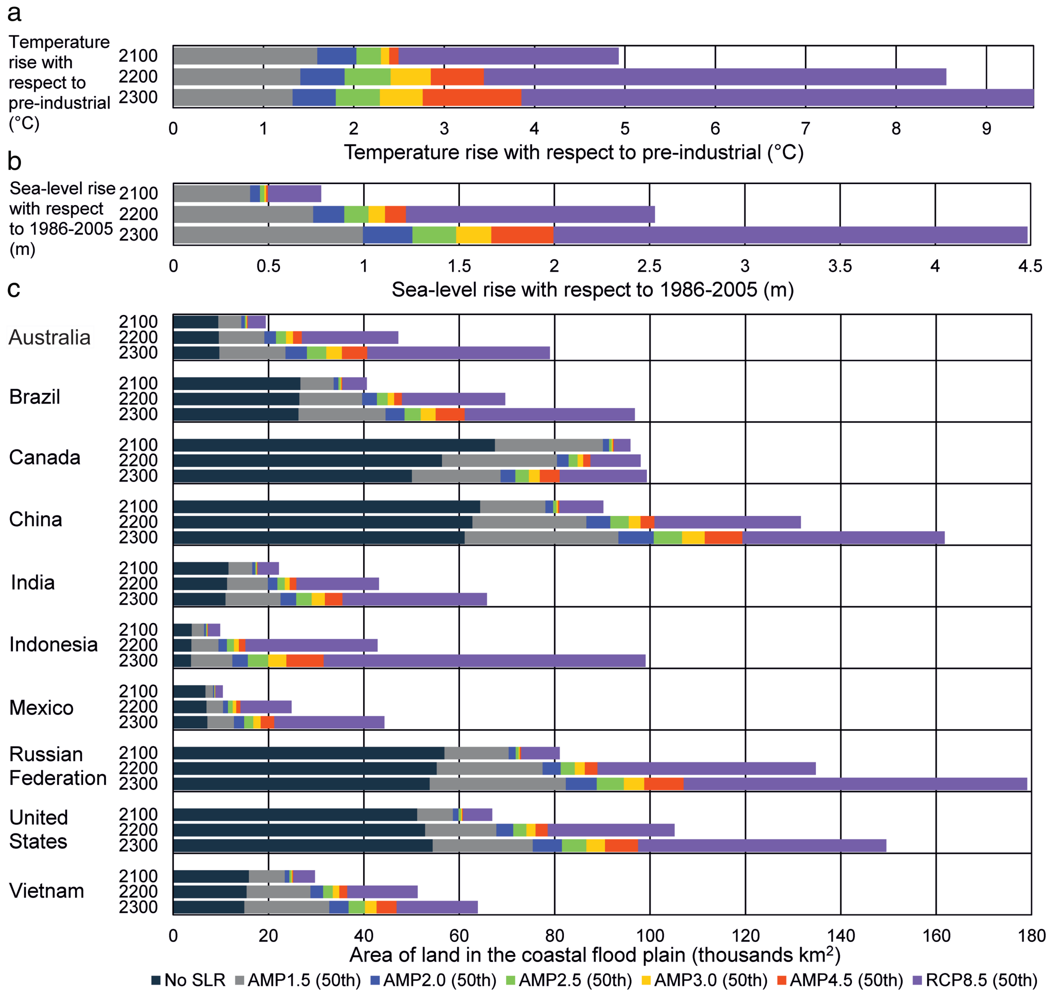

Figure 6. (a) Temperature rise for each climate change scenario. (b) SLR for each climate change scenario. (c) The top 10 country level exposure for the area in the 1 in 100 year coastal flood plain in 2100, 2200, and 2300 for each AMP and RCP8.5 (50th percentile).

per climate scenario and percentile uncertainty), plus the population change projected per entire country in 2100. These nations were selected as they have a large area of land and/or changing populations exposed to SLR.

In China, 5%–12% (AMP1.5 5th percentile to RCP8.5 95th percentile) of the population is at risk from SLR as many live in low-lying delta plains. The number of people exposed would particularly increase under an AMP4.5 and a RCP8.5 scenario, even with today's population. The uncertainties due to SLR mean that there are overlaps between the proportions of people exposed per climate change scenario. For example, under AMP1.5 (99th percentile) and AMP4.5 (50th percentile) 7% of population are projected to be exposed. While the magnitude of SLR is important, it is also important to consider the path dependency of SLR (see Section 5.1). By 2100, population is projected to decline (Figure 7e, with a percentage difference between 2100 and 2020 of −18% to −57%). Previous studies (e.g., Nicholls et al., 2010) indicate that even if populations decline, damage costs will remain high (assuming a basic level of protection) as significant investment has already been made in infrastructure and gross domestic product per capita is expected to continue to increase. Therefore, despite declining populations, damage in nations such as China is projected to be relatively large and likely continuing to increase in monetary terms.

In Iraq, the proportion of population exposed to flooding under the lowest scenario in AMP1.5 is 4%. A very large increase is projected under RCP8.5 (up to 12% of population in 2020). However, Iraq is also projected to have a large population growth under all scenarios, particularly SSP3 and SSP4 (Figure 7f). Large population

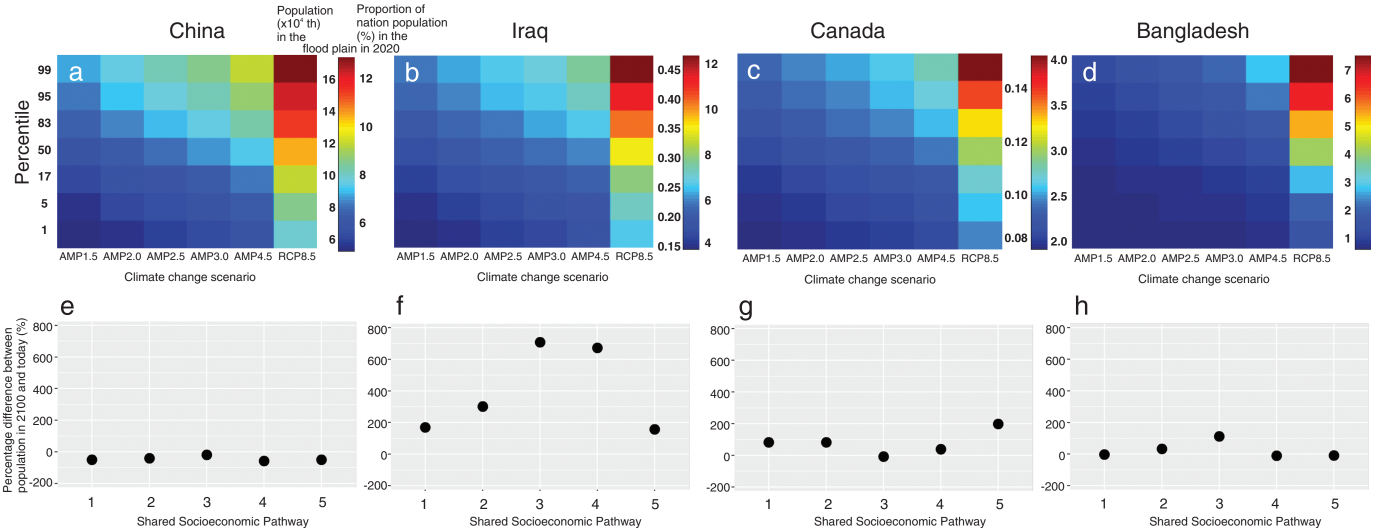

Figure 7. Population in the 2020 1 in 100 year coastal flood plain and proportion of national population taking account of climate change scenario and percentile uncertainty in 2300 for (a) China, (b) Iraq, (c) Canada, (d) Bangladesh. Population projections (at national level) in 2100 per socioeconomic change scenario for (e) China, (f) Iraq, (g) Canada, (h) Bangladesh. Note exposure plots have differing scales.

growth may mean the emergence of new cities, rather than expanding cities, as seen in the Middle East and China in recent decades. Large population growth combined with SLR in areas of low elevation could dramatically increase flood risk. Effective land use planning could encourage growth away from land in the coastal flood plain, meaning a reduction in the number of people exposed over the long term. Thus in nations where population is expected to grow, there are opportunities to divert this growth away from threatened areas. However, in practice this may be challenging to do.

In Canada, population exposed under the climate change mitigation scenarios is limited as many parts of the coast are uplifting in response to glacial isostatic readjustment. Additionally, the north-eastern coast is projected lower than average SLR due to the regional variation (Figure 1c). Within the countries presented in Figure 7, it is the least responsive to SLR. Large populations may not be affected unless there is a high rate and magnitude of SLR (e.g., RCP8.5 95th percentile would expose just 4% of the population in 2020).

In Bangladesh, the population exposed to flooding is sensitive to SLR and a high proportion of the population is affected, even under the climate change mitigation scenarios where 17% of the 2020 population would be exposed to flooding (AMP4.5 99th percentile). Therefore adaptation planning is essential regardless of the magnitude of SLR, particularly as population in 2100 is projected to remain similar to 2020 or increase.

This analysis indicates that some nations will be more prone to varying magnitudes of SLR than others, which reinforces earlier analyses into nations' areas in low elevation coastal zones (Lichter et al., 2010; Neumann et al., 2015). These studies also indicated a high level of exposure in east and south-east Asia. Importantly, under the non-mitigation scenarios all nations will experience significant changes compared with the mitigation scenarios so will need to consider the long-term implications of SLR.

5. Uncertainties and Implications

5.1. Data Uncertainties

So far, the source of uncertainty has focused on the drivers of change—climate and socioeconomic change. While there is considerable uncertainty in each AMP scenario, meaning that the scenarios overlap (see Section 2.1), the path dependency of these scenarios must be carefully considered as future SLR is dependent on emissions. This has important implications for policy (see Section 5.2).

The results presented involve uncertainties in input data and processing. Uncertainties in modeling low elevation landscapes include topographic and population models, subsidence, sources of flooding, shoreline dynamics, hydrodynamic response including tides, wetland change and migration and land use types (e.g., Passeri et al., 2015).

We have used SRTM topographic data (Jarvis et al., 2008), with vertical resolution of 1 m. Alternative topographic data (e.g., Global Land 1 km Base Elevation [GLOBE] dataset) could result in a greater magnitude of land being exposed. Hinkel et al. (2014) found the number of people flooded according to the GLOBE elevation model to be double to that calculated when using the SRTM elevation model. With differing population datasets however, Hinkel et al. (2014) found a similar number of people flooded. Equally, Wolff et al. (2016) found that modeling impacts at a finer resolution (e.g., coastal length, elevation) can have an influence, leading to higher estimates of impacts. Hence the results in this article indicate a relative change to today's elevation models, simultaneously acknowledging that large uncertainties exist.

Although the focus of this article has been quantifying exposure to SLR at 1.5°C and 2.0°C, we acknowledge that other drivers of flooding exist. Spatial changes to storminess could potentially alter spatial exposure at a finer level than presented here, whereas an increase in cyclone intensity could increase the number of people exposed to flooding. We have not considered any change in the storm surge climatology. This is because considerable uncertainty remains in regard to future changes in the frequency, magnitude, and tracks of storms with climate change and thus there is low confidence about how the storm surge climate may alter over time.

Subsidence can locally be a major increase in flood risk (Syvitski et al., 2009). For example, in Thailand, subsidence due to water pumping was as much as 120 mm/year in the 1980s before mitigation measures were instigated (Phien-wej et al., 2006). This locally had a greater effect on flood risk than SLR. Similarly, in the Ganges-Brahmaputra delta, large spatial and temporal uncertainties exist into the magnitude of subsidence (Brown & Nicholls, 2015), which exert a greater local influence on flooding than SLR.

The amount of land or the number of people exposed may increase if coastal fluvial flooding (e.g., adjacent to estuaries) is also considered (Ikeuchi et al., 2017; Moftakhari et al., 2017). However, the number of people at risk may be reduced through defenses, with potentially reductions by at least an order of magnitude (e.g., Hinkel et al., 2014; Nicholls et al., 2011) depending on the standard of defense. Hence exposure and risk should not be confused, although exposure always indicates potential or worst-case impacts if defenses fail.

Despite a large number of uncertainties, the value of this global study indicates regions or countries with high relative exposure (and potential impacts) to determine where resources or further research could be targeted. Population exposure is more relevant than land area exposure in this regard, but the uncertainties are significant. Finer scale resolution case studies, can help resolve many of these issues, as Wolff et al. (2016) demonstrated, but could increase uncertainty due to a multitude of datasets available. Regional or local studies (e.g., Huang et al., 2016) model processes in greater detail and often with finer resolution data. These help identify precise causes of flood exposure, potential losses with SLR and model solutions, thus potentially enabling actions to reduce flood risk to occur.

5.2. Benefits of Climate Change Mitigation in the Context of the Paris Agreement

To realize the benefits of the Paris Agreement (United Nations, 2015), policy makers would like to know the impacts of different mitigation targets. In 2050, when temperatures are between 1.7°C and 2.3°C (1.4°C and 2.5°C), with sea-levels between 0.20 and 0.24 m (0.14–0.33 m), the land exposed to coastal floods is very similar between all mitigation scenarios. Given the commitment to SLR, the true benefits of mitigation compared with a non-mitigation scenario are not realized until after 2100. Thus, policy makers need to appreciate that the long-term adverse implications of SLR from anthropogenic warming will not be realized when 1.5°C or 2.0°C warming is first achieved. Varying rates and magnitudes of sea-level change, combined with different topographic profiles and socioeconomic scenarios mean that relative exposure changes at different points in time for different countries worldwide. Furthermore if a range of methods to reduce flood risk are considered (e.g., engineering, spatial planning, insurance, preparedness), it is not possible to say that one SLR scenario over another represents a dangerous level of SLR. What is certain for all coastal nations, is that early mitigation is advisable and adaptation is also inevitably required.

Numerous modeling groups to date indicate that the Paris Agreement will be challenging to achieve, even accounting for the INDC goals (Raftery et al., 2017; Schleussner et al., 2016). The Paris Agreement does not explicitly mention the longevity of SLR (Nicholls et al., 2018) and therefore account for centennial scale adaptation. Presently, adaptation funding covers developing nations (including the least developed countries and small island developing States) as noted in the Kyoto Protocol (United Nations, 1998). However, as economies emerge and nations develop, their ability to contribute to adaptation shifts. Even by 2100, the state of international development will look very different than today. With no specific ending to the Paris Agreement, this could mean that nations will pay for coastal adaptation over centennial scales. Similar to previous research (e.g., Hardy & Nuse, 2016) this creates issues of responsibility following the "polluter pays" principle as high costs may occur for nations that were not high emitters when emissions peaked. Long-term national and international adaptation funding needs to be considered, particularly in nations that are sensitive to SLR.

Small islands are known to be highly vulnerable to climate change, particularly SLR (Albert et al., 2016; Nicholls & Cazenave, 2010; Nurse et al., 2014; Ourbak & Magnan, 2017; Storlazzi et al., 2015). While adaptation to SLR (including responsive or autonomous adaptation) is encouraged, the survival of some small island communities may be hinged on a multitude of extreme weather events. This was noted with the extensive damage in Barbuda during the hurricane season of 2017, where 90% of Barbuda's buildings were destroyed (Phipps, 2017). It may not be SLR that makes the difference in all communities, but high wind speeds and the difficulty of adapting to them may render islands uninhabitable in the short- or long-term. Thus climate change mitigation increases the chances of survival of small island communities, but does not guarantee this outcome without adaptation.

5.3. Responding to Sea-Level Rise

Given the long-term commitment to SLR there is an ongoing need to adapt which has rarely been considered (Nicholls et al., 2007, 2018; Wong et al., 2014). Adaptation commonly is defined under three categories (Dronkers et al., 1990): (1) protection (hard or soft measures to reduce the likelihood of inundation); (2) accommodation (develop policies or engineering to live with the consequences of SLR) and (3) retreat (a planned move coastline or assets landward).

Not all coasts will be protected and difficult decisions will need to be made in how to adapt. Which adaptation category is used is partly dependent on the physical and human setting. Populations may not wish to retreat, but in some settings this may be the only option. For instance, Kiribati has considered migration to Fiji (Chapman, 2012) and the Maldives have considered buying land in Sri Lanka (McKie, 2009). Today, islands such as Guna, Panama are already preparing to move (Pressly, 2017) to their mainland tenure. Where there are assets of high values, or relatively high values within one country, all means of adaptation will be considered, including accommodation and protection. In preparation for SLR, Boston, United States has considered coping strategies (Urban Land Institute, 2015) while the Netherlands have considered adaptation to SLR of up to 4 m by 2200 (Deltacommissie, 2008). Few studies have assessed limits of adaptation to SLR (Nicholls et al., 2015).

Aggressive mitigation will increase adaptation choices and give more time to plan. Small islands, deltas, and cities should be thinking about adaptation issues today and preparing adaptation plans. There are insufficient resources to optimally adapt all environments today, and this is unlikely to change. Wider forms of adaptation, such as insurance plus associated loss and damage, land use planning, or preparedness become increasingly important. International cooperation may be increasingly important (e.g., international cooperation to create barrages across rivers or seas, migration between countries).

6. Conclusions

Aggressive climate change mitigation will mean that the rate of SLR seen over the last century will continue to 2300, at least. If stringent climate change mitigation cannot be achieved, the rate of SLR is expected to accelerate, although the exact magnitude of rise remains uncertain. The uncertainties within a specific mitigation pathways can be large as no SLR scenario is distinct from an adjacent scenario during the timescale of this study, except RCP8.5. For the most stringent mitigation scenarios, the uncertainties are resolved sooner in time compared with the less stringent mitigation scenarios. Hence understanding uncertainties in projecting climate change and SLR remains important to consider.

For coastal zones affected by SLR, climate change mitigation will not deliver significant benefits until the 22nd century regardless of the amount of mitigation or the uncertainties in the modeling of climate change.

Early or aggressive mitigation will bring the most benefits over centennial scales. Similar areas of flood plain are projected to be exposed (particularly given uncertainties in scenarios) if temperatures stabilize at 1.5°C or 2.0°C at 2100 and further into the future. Therefore the area of land exposed to coastal flooding will increase, and will potentially more than double under a non-mitigation scenario compared with today's flood plain. Populations exposed to SLR may increase (depending on population projections) between 1.5% and 5.4% of global population in 2300 (1.2%–7.6%) (assuming no population growth after 2100).

Russia, China, and United States have the largest flood plain exposed to SLR. Nations will be sensitive to different magnitudes of SLR as their coasts have varying levels of elevation and different rates of land level change. For some nations, such as highly populated China, large numbers of people and infrastructure are exposed to flooding today and this will continue even if population declines. In other nations, such as Iraq, the number of people exposed will substantially increase due to projected population growth throughout the 21st century.

The commitment to SLR remains one of the greatest challenges of climate change, even if temperatures stabilize. Adaptation to SLR will remain essential for all coastal nations. The more stringent mitigation that takes place, the easier adaptation will be due to less exposure and more effective use of resources. All forms of adaptation need to be considered, particularly land use planning for nations where large population growth is projected or where coastward migration is expected.

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